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Research paper

Geochemistry and petrogenesis of Rajahmundry trap basalts of Krishna-Godavari Basin, India

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ABSTRACT

The Rajahmundry Trap Basalts (RTB) are erupted through fault-controlled fissures in the Krishna-Godavari Basin (K-G Basin) of Godavari Triple Junction, occurring as a unique outcrop sandwiched between Cretaceous and Tertiary sediments along the east coast of India. Detailed geochemical studies have revealed that RTB are mid-Ti (1.74–1.92) to high-Ti (2.04–2.81) basalts with a distinct quartz tholeiitic parentage. MgO (6.2–13.12 wt.%), $Mg^{\#}$ (29–50) and Zr (109–202 ppm) suggest that these basalts evolved by fractional crystallization during the ascent of the parent magma along deep-seated fractures. Moderate to high fractionation of HREE, as indicated by $(Gd/Yb)_N$ ratios (1.71–2.31) of RTB, suggest their generation through 3–5% melting of a Fe-rich mantle corresponding to the stability fields of spinel and garnet peridotite at depths of 60–100 km. Low K_2O/P_2O_5 (0.26–1.26), high TiO_2/P_2O_5 (6.74–16.79), La/Nb (0.89–1.45), Nb/Th $>$ 8 (8.35–13), negative anomalies at Rb reflect minimum contamination by granitic continental crust. $(Nb/La)_{PM}$ ratios (0.66–1.1) of RTB are attributed to endogenic contamination resulted through recycling of subducted oceanic slab into the mantle. Pronounced Ba enrichment with relative depletion in Rb indicates assimilation of Infra- and Inter-trappean sediments of estuarine to shallow marine character. Geochemical compositions such as Al_2O_3/TiO_2 (3.88–6.83), medium to high TiO_2 (1.74–2.81 wt.%), positive Nb anomalies and LREE enrichment of these RTB attest to their mantle plume origin and indicate the generation of parent magma from a plume-related enriched mantle source with EM I signature. Ba/Th (46–247), Ba/La (3.96–28.51) and Th/Nb (0.08–0.13) ratios suggest that the source enrichment process was marked by recycling of subduction-processed oceanic crust and lithospheric components into the mantle. Zr/Hf (37–41) and Zr/Ba (0.51–3.24) indicate involvement of an asthenospheric mantle source. The Rajahmundry basalts show affinity towards FOZO (focal zone mantle) and PSCL (post-Archaean subcontinental lithosphere) which reflect mixing between asthenospheric and lithospheric mantle components in their source. Origin of RTB magma is attributed to plume-lithosphere interaction and the upward movement of melt is facilitated by intrabasinal deep-seated faults in the K-G Basin.

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1. Introduction

The late Cretaceous–early Tertiary Rajahmundry Trap Basalts (RTB) of the Krishna-Godavari Basin extends ~60 km on either side of the Godavari River, north of the city of Rajahmundry in Andhra Pradesh, India (Baksi et al., 1994; Baksi, 2001; Sen and Sabale, 2011). The RTB have been considered as the eastward continuation of Deccan Traps thus representing an example of long distance lava transport spanning over 1500 km across India and about 70 km into the Bay of Bengal (Jay, 2005; Jay and

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Widdowson, 2008; Keller et al., 2008; Self et al., 2008). These traps are the only known outcrops of basalt flows along the east coast of India, coeval with the Deccan Traps. Recent work by Lakshminarayana et al. (2010) has brought to light the stratigraphic framework, flow morphology and volcanological features of the Rajahmundry Trap lava flows. In quarries of the Pangidi-Rajahmundry area, three distinct basalt flows interbedded with two Intertrappean sedimentary horizons are observed, which are in turn underlain by the late Cretaceous fossiliferous limestone bed (Infratrappean) and overlain by the Cenozoic Rajahmundry Formation (conglomerate/sandstone). The fossiliferous Infratrappean bed represents a marker zone of K-Pg (Cretaceous–Paleogene) boundary mass extinction. Ar-Ar geochronological data have established that the RTB (~64 Ma) are contemporaneous with the Deccan Traps (65–66 Ma) that records voluminous volcanic activity on the Indian subcontinent marking the catastrophic events at K-T boundary (Baksi et al., 1994; Allegre et al., 1999; Pande et al., 2004; Sheth, 2005). However, detailed petrological and geochemical studies of the RTB are lacking till date to appraise their genesis and mode of emplacement. This paper presents new geochemical (major, trace and rare earth elements) data for the RTB in order to elucidate (i) the petrogenetic processes associated with their evolution and (ii) implications on their emplacement in terms of regional tectonic framework.

2. Geological setting

The RTB are located along the southeastern part of the Godavari Triple Junction (Fig. 1A). The NW–SE trending Godavari Rift and the NNE–SSW to NE–SW oriented K-G Basin represents a tectonic junction known as Godavari Triple Junction. This terrane preserves a geological record spanning Mesoproterozoic to Neogene and provides evidences for Gondwana break-up, Cretaceous continental rifting and drifting (Lakshminarayana, 1996, 2002; Lakshminarayana et al., 2010). A series of NE–SW trending mounds present between Duddukuru and Rajahmundry, covering an area of ~100 km^2, represent the RTB (Fig. 1A) in the Krishna-Godavari Basin (K-G Basin). The development of K-G Basin has been controlled by a phase-wise uplift of the basement (Eastern Ghat Mobile belt) during Phanerozoic. Lakshminarayana (1995a) suggested that a series of NE–SW step faults controlled the development of east coast basins since Mesozoic. From west to east, these blocks are the Mailaram high, Dammapeta Basin, Raghavapuram Basin and Pangidi-Rajahmundry Basin (Fig. 1A). The Mailaram high was uplifted first during early Mesozoic and controlled the sedimentation pattern in the Dammapeta Basin. Due to post Jurassic uplift, the Mailaram high became a watershed and resulted in the development of short headed fan delta streams flowing towards east (Lakshminarayana, 1997) for the first time. RTB is exposed in three separate areas, namely Nallajerla, Pangidi and Rajahmundry separated by younger sediments (GSI, 1996). The occurrence of prominent outcrops is recorded in Pangidi and Rajahmundry and the Rajahmundry Trap lava flows occur as a single unit (Lakshminarayana, 1995b). The Pangidi-Rajahmundry area of K-G Basin exposes coastal Gondwana sediments (Cretaceous), RTB (K-Pg boundary), Rajahmundry Formation (Paleogene) and the Quaternary sediments (Table 1) (Fig. 1B). The uppermost horizons of the Tirupati Formation, forming the basement of the RTB, are represented by sandstone, clay and limestone and are known as the 'Infratrappean beds' which in turn are unconformably overlain by the RTB (Lakshminarayana et al., 1992). The RTB are bounded by a prominent NE–SW fault along the northwestern margin and overlain by the Cenozoic Rajahmundry Formation and Quaternary sediments in the east. NW–SE lineaments/faults traverse the traps at Duddukuru and Pangidi (Fig. 1B). The entire succession of RTB is preserved between these two faults.

Our present work deals with the well-exposed succession of RTB from the Gowripatnam (17°1′55.8″N, 81°37′41″E) and Duddukuru (17°2′2.2″N, 81°35′33.3″E) quarries, located west of the Godavari river. The RTB units here comprise of three distinct basaltic lava flows (lower, middle and upper) separated by two Intertrappean sedimentary horizons identified as Intertrappean I and II. The 20–30 m thick lower flow unconformably overlies the Maastrichtian-Danian Infratrappean bed (Fig. 2A). The lower basalt flow is characterized by the presence of physical volcanological features such as rootless cones, tumuli and dyke like forms along with prominent development of single to multi-tier columnar (Fig. 2B) and radial jointing (Fig. 2C). Intertrappean I consists of ~2–3.5 m thick clay, marl and limestone intercalations which is sandwiched between the lower and middle flows of RTB (Fig. 2A). Several invertebrate fossils have been collected from this limestone horizon at Pangidi and Rajahmundry areas and this palaeontological evidence has received great attention in view of their similarity with the Intertrappean beds of western and central India (Lakshminarayana et al., 2010; Malarkodi et al., 2010). The middle flow represents 6–10 m thick, greenish grey vesicular basalt resting unconformably over the clay and limestone of Intertrappean I. This flow is 1–2 m thick and appears to be massive. The middle flow is overlain by Intertrappean II which is made of red clay/red bole. The upper flow (5–17 m thick) unconformably overlies the Intertrappean II and is made of fine-grained vesicular basalt.

3. Petrography

The lower, middle and upper flows of RTB are characterized by phenocrysts of plagioclase and clinopyroxene. Groundmass is generally marked by tiny plagioclase, granular pyroxene, opaque minerals and glass. Plagioclase phenocrysts are dominant and are mostly lath-shaped (Fig. 3A). Clinopyroxene phenocrysts are mostly prismatic and occur as individual medium-sized subhedral grains, and clusters of microphenocrysts. These clustered clinopyroxene microphenocrysts have been designated as tecoblast (Pattanayak and Srivastava, 1999; Ganguly et al., 2012). Euhedral olivine phenocrysts are minor and are partially or completely altered to palagonite and iddingsite. These are secondary constituents derived mostly by the hydrous alteration of the primary mafic minerals. The lower and middle flows exhibit vesiculation features containing abundant vug infillings and a greater proportion of groundmass glass, whereas the upper flow is massive with lesser vesicles. Devitrification is also observed at some places. The overall textural pattern is intersertal and intergranular (Fig. 3B). Distinct development of clustered plagioclase phenocrysts represents glomeroporphyritic texture (Fig. 3A). Some sections have the presence of secondary carbonates.

4. Analytical techniques

Least altered samples of trap basalts, collected from three lava flows, were selected for detailed geochemical studies. Forty-two samples were analyzed for major, trace and rare earth elemental compositions. Rocks were powdered using an agate mortar. Major elements were analyzed by XRF (Phillips MAGIX PRO Model 2440), with relative standard deviations <3%. For rare earth elements (REEs), HFSE and other trace elements, powders were dissolved in reagent grade HF and HNO_3 in Savillex screw top vessels, using the procedure of Manikyamba et al. (2012), and determined by ICP-MS (Perkin Elmer SCIEX ELAN DRC II) at the National Geophysical Research Institute (NGRI), Hyderabad. Certified reference materials JB-2 and BHVO-1 were run as standards along with the samples given basaltic compositions of major, trace elements and REE. The analyses and RSD values of JB-2 and BHVO-1 are given in Table S1.

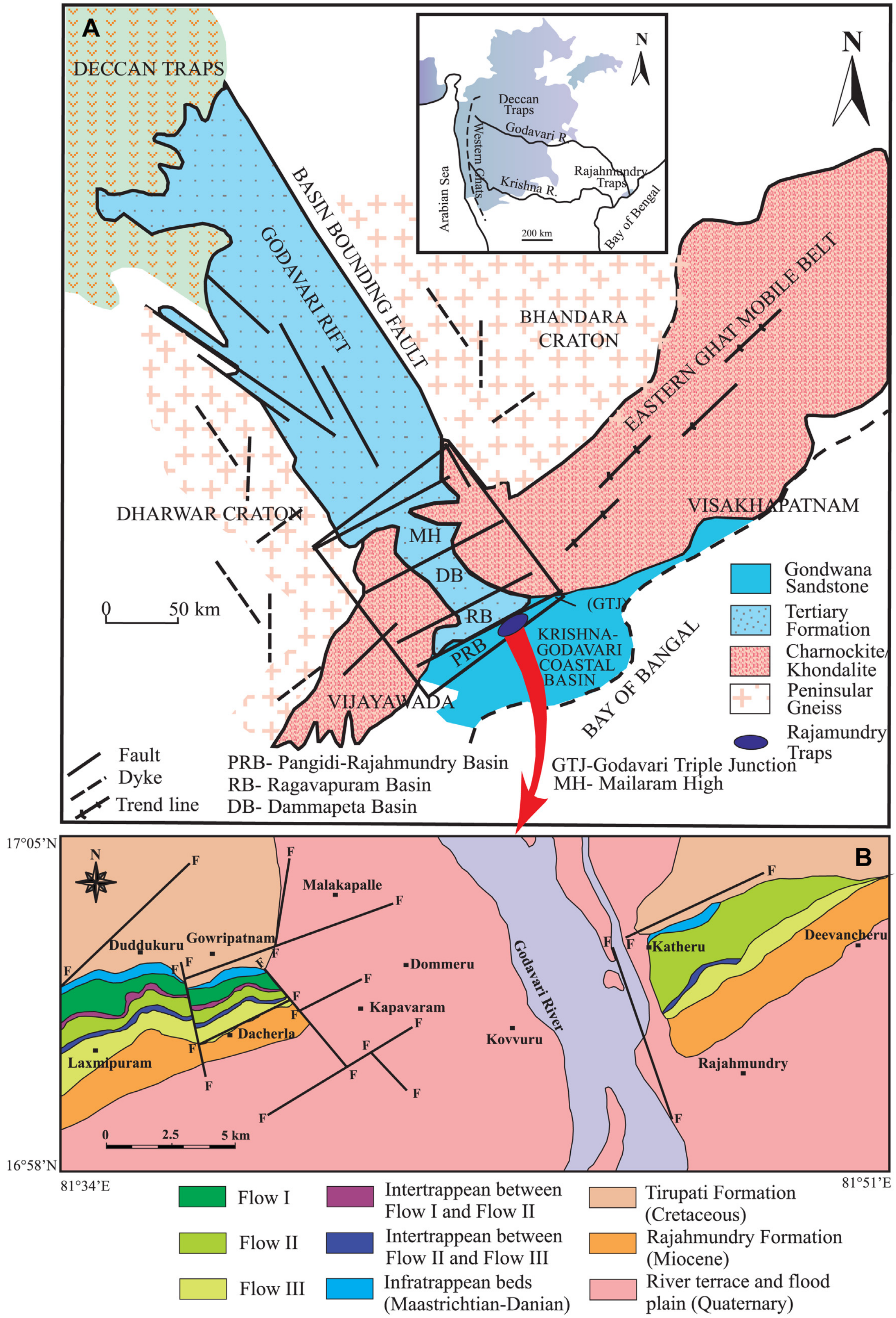

Fig. 1. (A) Geological map of Godavari Triple Junction (GTJ) showing the location of Rajahmundry Trap basalts (RTB) with respect to Godavari Rift, K-G Basin and Eastern Ghat Mobile Belt (EGMB). Inset map shows the areal extent of Deccan Traps and RTB in Peninsular India (after Self et al., 2008). (B) Generalized geological map of the Rajahmundry Trap basalts showing distribution of three lava flows with associated inter- and infratrappean sediments.

Table 1
Stratigraphic succession of the Rajahmundry Traps.

Formation	Lithology	Age
Rajahmundry	Conglomerate, sandstone, clay and lignite	Eocene/Miocene (Tertiary)
	Unconformity	
Rajahmundry Traps	Upper Trap (basalt)	K/T boundary
	Intertrappean II (clay)	
	Middle Trap (basalt)	
	Intertrappean I (clay, limestone and marl)	
	Lower Trap (basalt)	
	Unconformity	
Beds (Tirupati Formation)	Sandstone, clay and limestone	Maastrichtian (late Cretaceous)

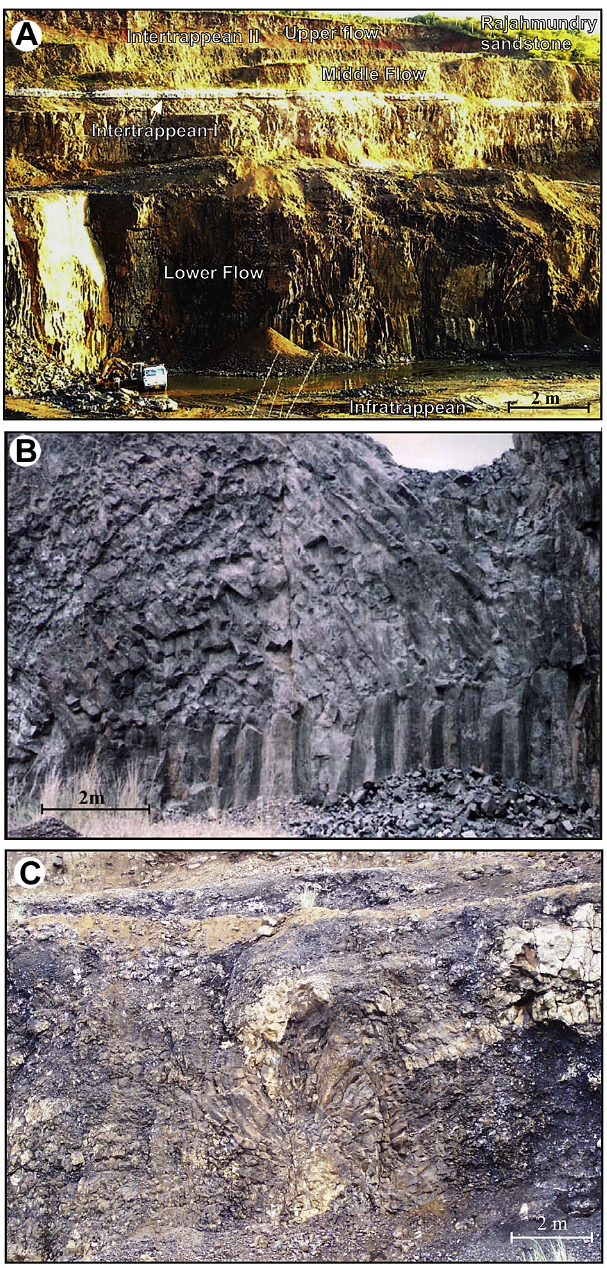

Fig. 2. Field photographs of (A) lower, middle and upper flows of RTB separated by Intertrappean I and II, (B) single to multi-storeyed columnar joints in the lower flow and (C) lower flow exhibiting radial jointing pattern.

Fig. 3. Photomicrographs showing (A) clustered plagioclase phenocrysts forming glomeroporphyritic texture; zoning is observed in a single plagioclase phenocryst and (B) intersertal and intergranular texture in Rajahmundry Trap Basalts (RTB).

5. Geochemistry

5.1. Major elements

The RTB show SiO_2 content ranging from 47.45 to 50.58 wt.%, moderate to high MgO and CaO (6.19–13.12 wt.% and 6.85–10.58 wt.% respectively, Table S2). Al_2O_3 content shows a narrow range between 10.88 and 12.49 wt.% (Table S2) and distinctly depict the tholeiitic character. The rocks are typically enriched in Fe with 7.56–10.29 wt.% FeO. The K_2O content ranges from 0.05 to 0.30 wt.% and in terms of SiO_2 vs. K_2O, the Rajahmundry Trap basalts are low-K sub-alkaline tholeiites (Fig. 4A). The TiO_2 content of RTB ranges from 1.74 to 2.81 wt.%. These are classified as mid-Ti basalts ($TiO_2 \leq 2.0$ wt.%) and high Ti-basalts ($TiO_2 \geq 2.0$ wt.%) where 2 wt.% of TiO_2 has been considered as the boundary keeping in view of the compositional range of plume-related basalts around the world erupted in both continental and oceanic environments (Safonova, 2009; Simonov et al., 2014). Accordingly, the mid-Ti basalts of Rajahmundry have TiO_2 content ranging from 1.74 to 1.92 wt.%, while the high-Ti basalts have TiO_2 content of 2.04–2.81 wt.%. Geochemical parameter used for constraining magmatic differentiation like Differentiation Index (D.I.) (Thornton and Tuttle, 1960) shows a wide range of variation from 39 to 52 which corroborates middle to late stage magma differentiation (Cox, 1980; Wilson, 1989). The major element compositions of RTB are consistent with that of tholeiitic basalts of Deccan Traps and Ocean Island Basalts (OIB; Hughes, 1982; Sun and McDonough, 1989; Table S2). CIPW normative compositions (Table S2) are marked by the presence of quartz (4.02–9.89 wt.%) and

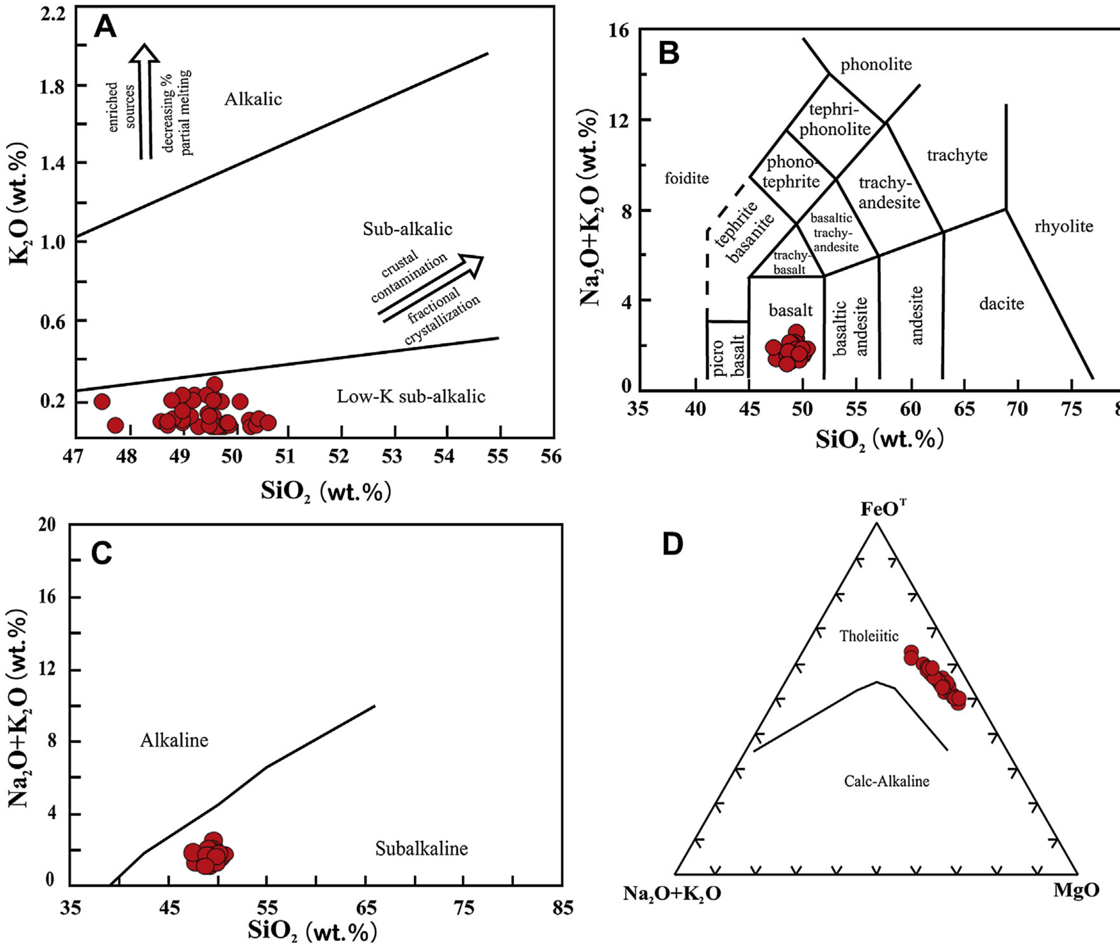

Fig. 4. (A) SiO_2 vs. K_2O plot depicting a low-K sub-alkalic nature of Rajahmundry Trap Basalts (RTB). Field boundaries are from Middlemost (1975). (B) Total alkali ($Na_2O + K_2O$) vs. silica (SiO_2) diagram (after Le Bas et al., 1986; Le Maitre, 1989) showing the Rajahmundry samples in the field of Basalt. (C) Total alkali ($Na_2O + K_2O$) vs. silica (SiO_2) diagram (after McDonald and Katsura, 1964) showing the subalkaline composition of RTB and (D) Rajahmundry Trap Basalts (RTB) showing a distinct tholeiitic trend in ($Na_2O + K_2O$)–FeO^T– MgO (AFM) diagram (after Irvine and Baragar, 1971).

hypersthene (16.18–35.25 wt.%). A silica-oversaturated, quartz tholeiitic character of the RTB can be adjudged from the normative mineralogy. In the total alkali ($Na_2O + K_2O$) vs. silica (SiO_2) diagrams (Le Bas et al., 1986; Le Maitre, 2002, Fig. 4B and C) the samples plot in the field of basalt (Fig. 4B) showing a sub-alkaline composition (Fig. 4C). These basalts exhibit a distinct tholeiitic trend in the AFM diagram (after Irvine and Baragar, 1971, Fig. 4D). Abundances of major element oxides such as MgO, CaO, Fe_2O_3, and TiO_2 show a negative correlation with increasing D.I. while Al_2O_3, Na_2O and K_2O contents show a positive correlation with D.I. (figures not shown).

5.2. Trace elements

The Rajahmundry Trap basalts are characterized by depletion in compatible elements (Ni, Cr), and relative enrichment in incompatible elements like Large Ion Lithophile Elements (LILE) and Light Rare Earth Elements (LREE; Table S2). Ni (74–129 ppm) and Cr (76–235 ppm) concentrations of RTB are lower than that of primary mantle melts (Ni > 200 ppm, Cr > 400 ppm). Sc (36–43 ppm) concentrations point towards crystallization of clinopyroxene phenocrysts which trap sufficient Sc (Albarede, 1995; Albarede et al., 1997). These basalts have relatively lower Rb (0.9–11.1 ppm) and Sr (235–315 ppm) as compared to OIB (Rb: 31 ppm; Sr: 660 ppm) compositions (Table S2). Ba is widely variable (54–262 ppm) and reaches up to 262 ppm with respect to 350 ppm in OIB (Table S2). These basalts have relatively lower Nb and Ta concentrations (6.9–15.37 ppm and 0.5–1 ppm respectively) in comparison with that of OIB (Nb: 48 ppm; Ta: 2.7 ppm; Table S2). Primitive mantle-normalized (Sun and McDonough, 1989) multi-element patterns for RTB (Fig. 5) show consistent trace element characters suggesting an overall geochemical coherence among the three lava flows. The RTB samples depict positive Ba and Th anomalies and distinct negative anomalies at Rb and K with minor to negligible Sr anomalies. The HFSE patterns show positive Nb-Ta anomalies. Negative P, Ti and Yb anomalies are also evident on multi-element diagram. Chondrite normalized REE patterns exhibit pronounced LREE enrichment (Fig. 5), highly fractionated HREE patterns and minor to negligible Eu anomaly.

6. Petrogenesis

6.1. Crustal contamination

Compositional variations in mantle-derived magmas have been attributed to variable amounts of contamination by different crustal components during their ascent to the surface through continental crust (Hawkesworth et al., 1984; Mahoney, 1988; Carlson, 1991; Hergt et al., 1991; Arndt and Christensen, 1992; Gallagher and Hawkesworth, 1992; Saunders et al., 1992; Arndt

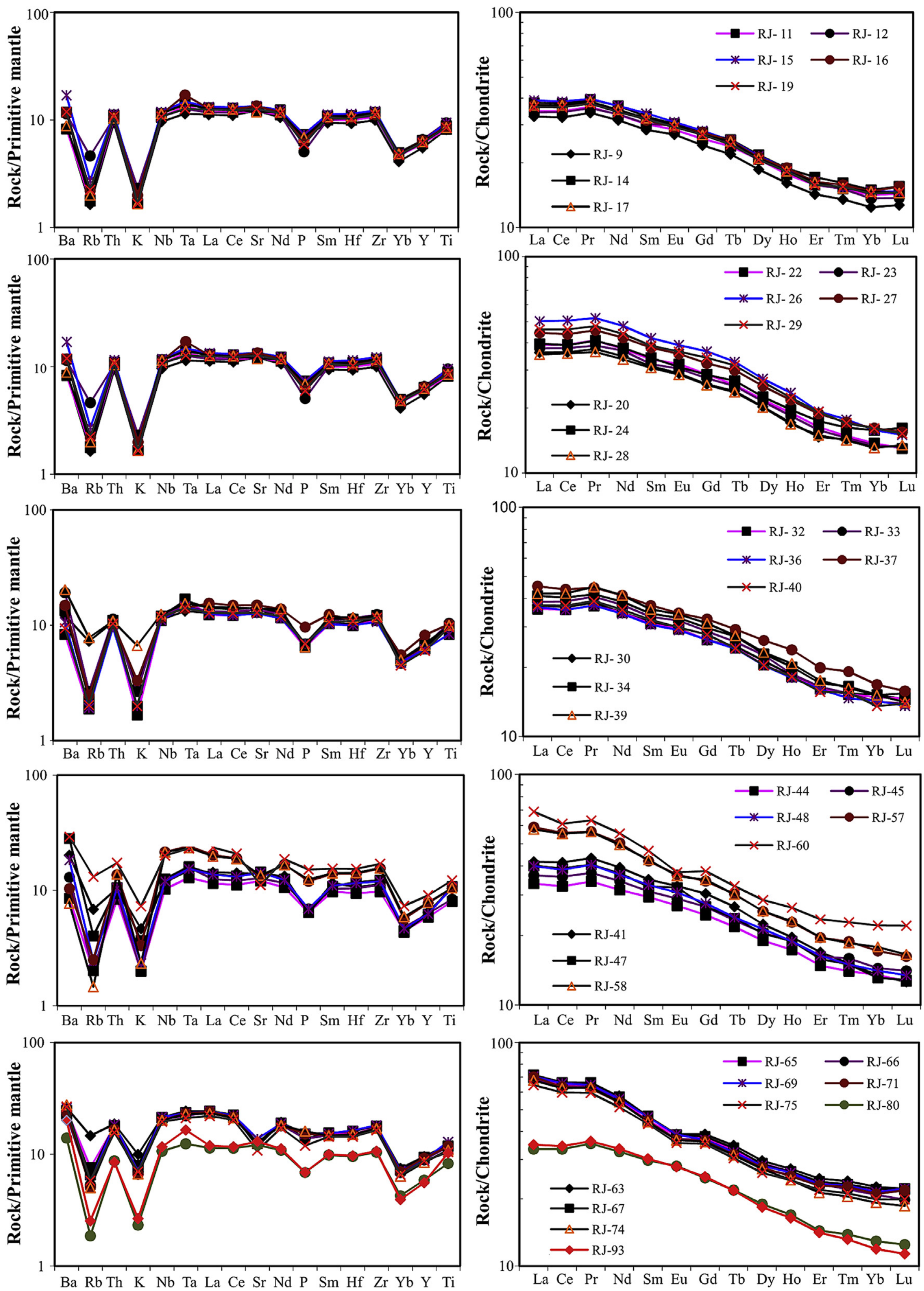

Fig. 5. Primitive mantle-normalized multi-element spider diagram and Chondrite-normalized REE patterns for the Rajahmundry Trap Basalts (RTB) (normalization values are from Sun and McDonough, 1989).

et al., 1993; Sweeney et al., 1994; Song et al., 2001, 2008). The basalt flows of Rajahmundry Traps have relatively low K_2O/P_2O_5 (<2) having a range of 0.26–1.26. This feature indicates minimum involvement of silicic crustal component or wall rock (of granitic composition) assimilation during their ascent and storage of the flood basalt magmas. The relatively high TiO_2/P_2O_5 (6.74–16.79) for RTB are compatible with an intraplate OIB source, least affected by contamination from granitic continental crust (Carlson and Hart,

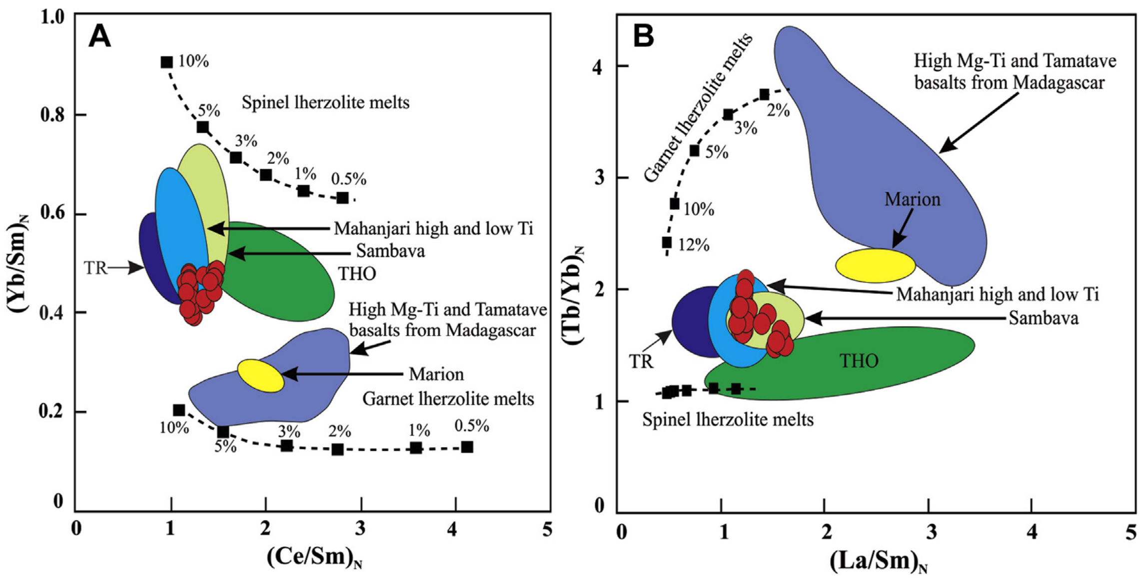

Fig. 6. (A) Plots of $(Ce/Sm)_N$ vs. $(Yb/Sm)_N$ variations for Rajahmundry basalts in comparison with Madagascan volcanic (after Radhakrishna and Joseph, 2012). The compositions of aggregated melts produced by different degrees of melting of a spinel lherzolite and garnet lherzolite sources are shown. Details of model calculations are as given in Storey et al. (1997). (B) $(La/Sm)_N$ vs. $(Tb/Yb)_N$ diagram for Rajahmundry basalts in comparison with Madagascan volcanic rocks (after Radhakrishna and Joseph, 2012). Details of melting curves and calculations are referred to Melluso et al. (2001).

1988). The marked depletion of Rb in the studied samples also suggests minimum possibility of contamination from continental crustal materials. Thompson et al. (1984) considered La/Nb ratio as a suitable index of crustal contamination in magmas and suggested that OIB, continental alkali basalts and kimberlites have La/Nb < 1, while that in CFB magmas range from 0.5 to 7. The La/Nb ratios (0.89–1.45) of the RTB are showing a restricted range with respect to that of CFB and this reflects limited crustal contamination of parent magma (Peate et al., 1999; Song et al., 2001). HFSE ratios are suitable indicators of crustal contamination in an open magma system. The studied basalts have relatively higher Zr/Nb and Th/Nb ratios (11–16 and 0.08–0.13 respectively) than those of the OIB (4.2 and 0.06 respectively; Hofmann, 1988; Ionov et al., 1997) and low $(Nb/La)_{PM}$ (0.66–1.1) which may be attributed to lower Nb concentrations compared to typical OIB (Hofmann, 1988; Mahoney et al., 1993; Safonova et al., 2008; Buslov et al., 2010; Manikyamba and Kerrich, 2011; Simonov et al., 2014). These low Nb contents do not represent the exogeneous contamination of tholeiitic melts by continental crust but reflect on endogenous contamination caused due to recycling of lithosphere (having depleted upper mantle materials) during subduction of oceanic slab into the mantle (Polat et al., 1999; Safonova et al., 2008). Low Th concentrations (0.71–1.58 ppm) along with Th/Ta ratios of RTB spanning from 1.07–1.85 support minimum crustal contamination (Safonova et al., 2008; Lai et al., 2012). The Nb/Th ratio of primitive mantle is 8, whereas in continental crust it is ~1.1 (Taylor and McLennan, 1985; Sun and McDonough, 1989; Rollinson, 1993). Rajahmundry basalts characteristically have Nb/Th > 8 (Nb/Th: 8.35 to 13 except one sample having Nb/Th: 7.7) which is consistent with that of primitive mantle values thereby reflecting minimum contamination of parent melt by continental crust. Primitive mantle-normalized multi-element patterns of RTB (Fig. 5) marked by positive Ba anomalies (Ba: 54–262 ppm) and distinct Rb troughs (Rb: 0.9–11.1 ppm) imply minimum input from granitic continental crust and indicate contamination of the parent magma during its migration to the surface by variable amounts of assimilation of Ba-rich Infratrappean and Intertrappean sediments of estuarine to shallow-marine character.

6.2. *Mantle melting conditions*

Rare-earth element compositions provide important constraints in understanding the mantle melting conditions because their relative abundances in mantle-derived melts are strongly dependent on the degree of partial melting and the nature of aluminous phase (spinel or garnet) in the mantle source (Lassiter et al., 1995; Reichow et al., 2005; He et al., 2010). In general, HREE especially Yb is compatible in garnet and has high garnet/melt partition coefficients, whereas La (LREE), Sm and Gd (MREE) are incompatible and have low garnet/melt partition coefficients (Irving and Frey, 1978; Kelemen, 1990; Rollinson, 1993). La/Yb and Sm/Yb are strongly fractionated when melting occurs in the garnet stability field and in contrast to this La/Yb is slightly fractionated and Sm/Yb is nearly unfractionated during melting in the spinel peridotite domain (Yaxley, 2000; Xu et al., 2005; Lai et al., 2012). Gd/Yb and Sm/Yb are distinct indicators of the presence of residual garnet during partial melting. The REE signatures of RTB marked by $(La/Yb)_N = 2.50–3.65$, $(Sm/Yb)_N = 2.06–2.66$ and $(Gd/Yb)_N = 1.71–2.31$ (Table S2) with chondrite-normalized REE patterns (Fig. 5) reflect moderate to high fractionation of HREE and thus suggest that the parental magmas were derived by partial melting of a mantle source at variable depths extending from spinel to garnet stability fields (Safonova et al., 2008; Buslov et al., 2010). Intercepts on melting curves on $(Ce/Sm)_N$ vs. $(Yb/Sm)_N$ diagram suggest that these basalts resemble with the tholeiitic and transitional series of volcanic rocks from the Mailaka and Bemaraha areas of central–western Madagascar (Radhakrishna and Joseph, 2012). These are spatially distributed in the region between spinel lherzolite and garnet lherzolite melts (Fig. 6A). Similar inferences are derived from $(La/Sm)_N$ vs. $(Tb/Yb)_N$ figure (Fig. 6B). Basaltic lavas are conventionally derived by mantle melting at depths shallower than ~100 km. It has been suggested that the source regions of continental flood basalt (CFB) magmatism are modified by contributions from both continental lithosphere and asthenosphere and the geochemical processes were occurring over tens of millions of years or more (Kürkcüoglu, 2010). In normal mantle, the transition from spinel to garnet peridotite occurs between ~60 and 80 km,

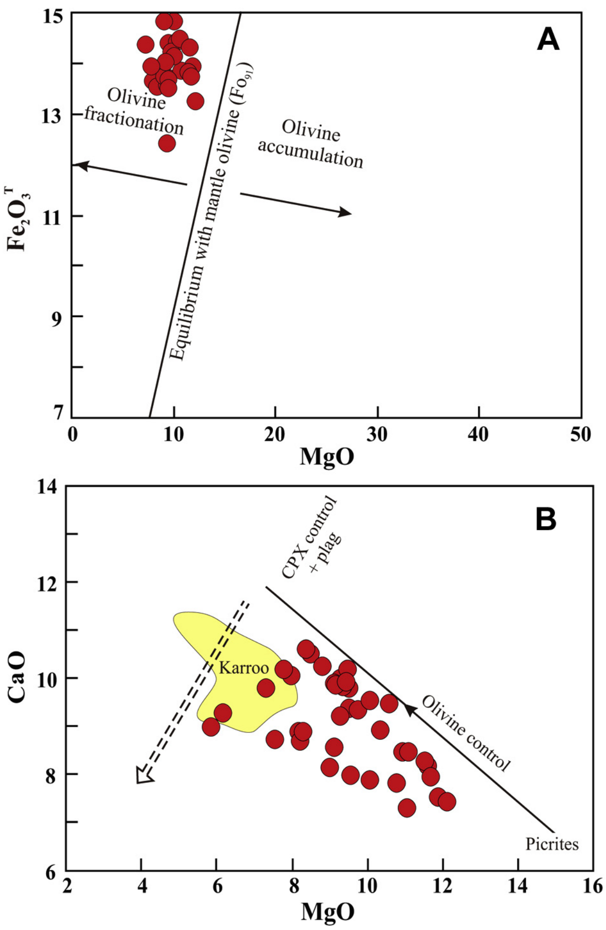

Fig. 7. (A) MgO vs. $Fe_2O_3^T$ variations showing a distinct olivine fractionation trend for Rajahmundry basalts. (B) MgO vs. CaO variations suggesting a plagioclase-clinopyroxene controlled fractional crystallization process for Rajahmundry basalts.

but in the presence of upwelling mantle plume, this depth may be 80–100 km (Sen, 1988; McKenzie and O'Nions, 1991; White and McKenzie, 1995). Therefore, the mantle melting conditions derived for the evolution of Rajahmundry Trap basalts suggest that these basalts were produced by 3–5% partial melting of a Fe-rich mantle regime extending from spinel to garnet peridotite compositional range at depths of 60–100 km.

6.3. Fractional crystallization

The lower, middle and upper flows of Rajahmundry Traps are inequigranular pheonocrystic basalts composed of clinopyroxene and plagioclase (and minor olivine) phenocrysts which indicate fractional crystallization of the parental magma before eruption. The variation trends of major oxides with respect to progressive differentiation of the melt corroborate a magmatic system dominated by fractional crystallization. The negative trends observed between MgO, CaO, Fe_2O_3 and D.I. indicate crystallization of ferromagnesian phases like clinopyroxene from the melt and the positive correlation of Al_2O_3 with D.I. suggests progressive crystallization of plagioclase. The overall major oxide compositions suggest that the mid- to high-Ti basalts of Rajahmundry are generated by magmatic fractionation process dominantly controlled by crystallization of plagioclase and clinopyroxene. Rajahmundry Trap basalts have MgO content of 6.19–13.12 wt.% and $Mg^{\#}$ varying between 29 and 50 which suggest an evolved chemistry of the flows marked by fractional crystallization of magma. Ni (74–129 ppm) and Cr (76–235 ppm) concentrations of RTB are lower than that of primary mantle melts (Ni > 200 ppm, Cr > 400 ppm) of an olivine dominated source, thereby carrying implications of widespread fractional crystallization processes and pronounced magmatic evolution. The RTB are products of extensive fractional crystallization of clinopyroxene-rich, olivine-poor melt with plagioclase, clinopyroxene as the dominant crystallizing phases and little or no olivine in the crystallizing mineral assemblage. This feature can be visualized through the MgO vs. $Fe_2O_3^T$ plot (Fig. 7A) where the samples depict distinct olivine fractionation trend in the parent magma. The CaO–MgO relationship suggests crystal-liquid control by clinopyroxene and plagioclase during fractional crystallization processes (Fig. 7B). RTB have relatively low $Mg^{\#}$ (29–50) attesting to their derivation from a mantle more Fe-rich than normal MORB-OIB compositions. The evolved nature of these basalts, negative correlation between $Mg^{\#}$ and incompatible trace element abundances, negative Sr anomalies and relatively high Zr contents are in agreement with the observation that these geochemical variations are a result of magmatic differentiation controlled by extensive fractional crystallization over a wide range of pressure. Mantle-normalized multi-element patterns and chondrite-normalized REE diagram show overall flat patterns for Sr and Eu respectively. These trace element and REE signatures of the plagioclase phyric RTB reflect pressure-sensitive crystallization of plagioclase and variations in melt water content during crystallization. It has been envisaged that values of $^{plagioclase/melt-}D^{REE}$ decreases as the melt H_2O content increases and as pressure drops, while values of $^{plagioclase/melt}D_{Sr}$ are sensitive to pressure (Bédard, 2006).

7. Discussion

7.1. Mantle source characters

Primitive mantle-normalized multi-element patterns and chondrite normalized REE patterns (Fig. 5) exhibit higher abundances of LILE and LREE of these basalts suggesting that their parent magma had a mantle source which had experienced sufficient enrichment in these elements. Zr/Hf, Zr/Sm and Nb/Ta ratios against respective primitive mantle values of 36, 25 and 17 attest to an enriched mantle source for the derivation of parent magma producing RTB. These basalts have Nb (6.9–15.37 ppm) and Zr (109–202 ppm) contents higher than those of the N-MORB (Nb = 2.33 ppm, Zr = 74 ppm) and lower than that of OIB (Nb = 48 ppm, Zr = 280 ppm) implying their generation from an enriched mantle source (Sun and McDonough, 1989). Trace element ratios like Zr/Nb, La/Nb, Ba/Nb/, Ba/Th, Rb/Nb, K/Nb, Th/Nb, Th/La and Ba/La maintain distinctive values corresponding to different mantle sources and provide constraints on the mantle source components (Weaver, 1991). The incompatible trace element ratios (Zr/Nb, La/Nb, Ba/Nb/, Ba/Th, Rb/Nb, K/Nb, Th/Nb, Th/La and Ba/La) for Rajahmundry Trap basalts (Table S3) are similar to those of EM I component and account for a parent magma which had an enriched mantle (EM I) source signature. The most convincing and viable explanation that accounts for the origin of enriched geochemical signatures of mantle plumes is recycling of ancient, subduction-processed, ocean- and continent-derived crustal and lithospheric components into the deep mantle (Hofmann and White, 1982; Sobolev et al., 2007; White, 2010; Cabral et al., 2013). Therefore, ancient subducted and recycled oceanic lithosphere carrying both oceanic and continental crustal materials seem to have contributed to the source region for plume-sourced OIB magmas and this can also be expected for CFB magmas as well (Sheth, 2005; Stracke et al., 2005; Garfunkel, 2008). The Ba/Th (46–247), Ba/La

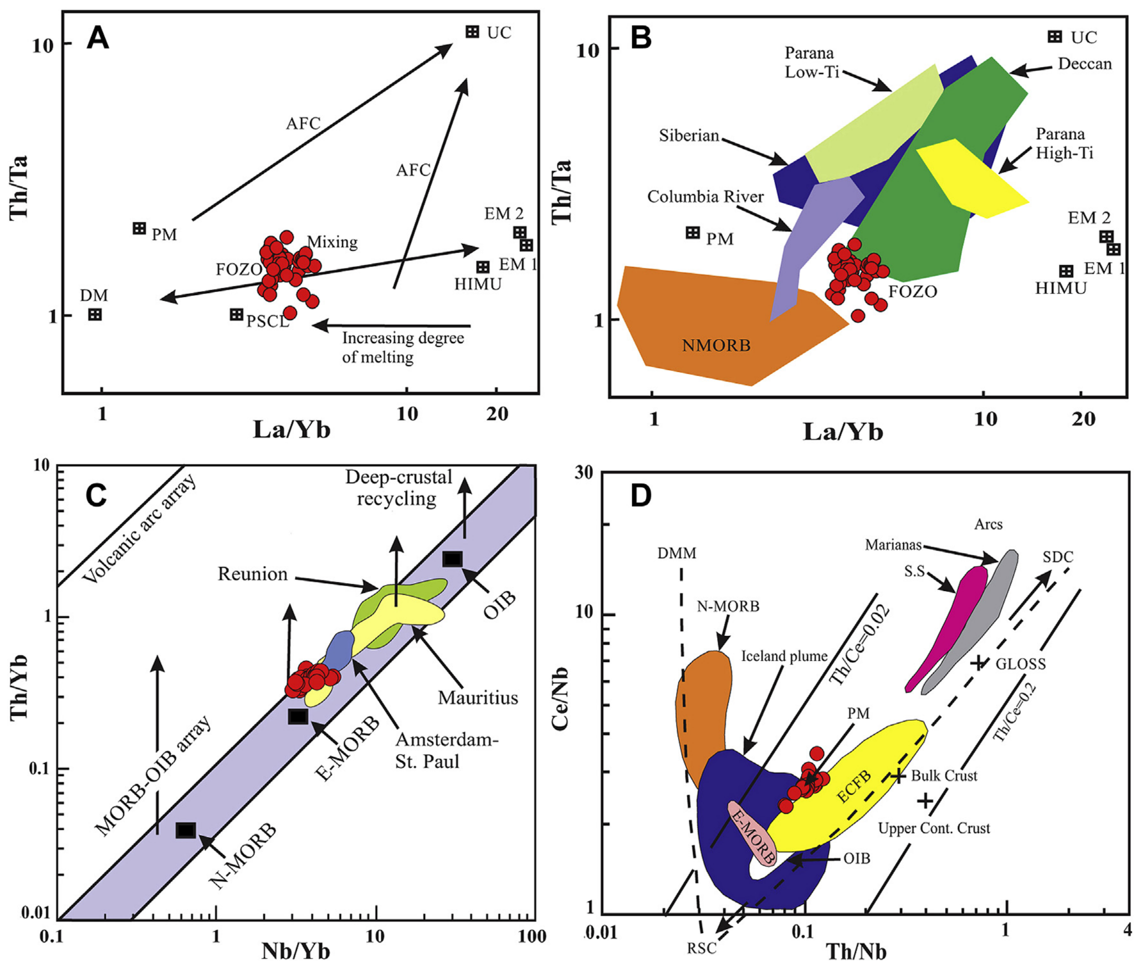

Fig. 8. (A) Th/Ta vs. La/Yb plot (after Condie, 2001) showing the plots of Rajahmundry basalts and the distribution of mantle components. DM: depleted mantle, PM: primitive mantle, PSCL: post-Archaean subcontinental lithosphere, FOZO: focal zone mantle, EM 1 and EM 2: enriched mantle sources, HIMU: high-mu source, UC: upper continental crust, AFC: assimilation-fractional crystallization trajectory. The Rajahmundry basalts show an enriched mantle source character and plot close to FOZO (defining a mixing between EM-HIMU and DM in the plume source) with an affinity towards PSCL. (B) Th/Ta vs. La/Yb plot (after Condie, 2001) in which the Rajahmundry basalts plot proximal to FOZO, close to the field of Deccan basalts and show distinct affinity towards PSCL. (C) OIB-MORB array in the Nb/Yb vs. Th/Yb diagram (after Pearce, 2008) showing minimum effects of crustal contamination and subduction in Rajahmundry basalts and the samples cluster in field of Amsterdam-St. Paul OIB. (D) Plots of Ce/Nb vs. Th/Nb for the Rajahmundry Trap Basalts (RTB), Emeishan Continental Flood Basalts (ECFB), depleted mantle (DMM), subduction component (SDC), ocean island basalts (OIB), normal mid-oceanic ridge basalts (N-MORB), enriched mid-oceanic ridge basalts (E-MORB), primitive mantle (PM), and the compositions of upper continental crust and bulk continental crust are from Saunders et al. (1988, 1991). Data for Iceland plume are from Hemmond et al. (1993). Fields for arcs are from Saunders et al. (1991). Global subducting sediment composition (GLOSS) after Plank and Langmuir (1998).

(3.96–28.51) and Th/Nb (0.08–0.13) ratios of RTB are consistent with a source carrying signatures of EM I which supports the contention of source enrichment by oceanic crust and lithospheric components recycled through ancient subduction processes (Weaver, 1991; Song et al., 2001). This conjecture is supported by the La/Yb vs. Th/Ta plot (Fig. 8A; after Condie, 1997) where the Rajahmundry Trap basalts belong to the FOZO (focal zone mantle) component mantle source. FOZO is referred as a plume component located in the lower mantle and commonly present in OIB magmas (Condie, 2001). Geochemical imprints like K/Na (0.03–0.22), K/La (43–169), K/Ti (0.04–0.16), K/Nb (50–245) and CaO/Al_2O_3 (0.59–0.89) suggest an OIB-like enriched mantle source for RTB. In the La/Yb vs. Th/Ta diagram (Fig. 8A) the Rajahmundry samples plot close to the field of Deccan basalts and point towards a strong FOZO component in their plume source. The proximity of the Rajahmundry samples to the FOZO and PSCL (post-Archaean subcontinental lithosphere) in La/Yb vs. Th/Ta plots (Fig. 8A and B) indicates mixing between asthenospheric and lithospheric mantle components thereby reflecting significant contribution from subcontinental lithosphere (Hart et al., 1992; Hauri et al., 1994) into plume-derived melts. The Rajahmundry basalts fall within the MORB-OIB array in Th/Yb vs. Nb/Yb diagram (Fig. 8C; Pearce, 2008) and the plots are clustered in a trend consistent with the fields of Amsterdam-St.Paul OIB basalts, Reunion and Mauritius lavas. In the Th/Nb vs. Ce/Nb diagram (Fig. 8D; Saunders et al., 1988) the RTB samples plot close to the fields of OIB and Emeishan CFB and lie between a recycled residual slab and a recycled subduction derived component. Low $(Nb/La)_{PM}$ ranging from 0.66 to 1.1 also supports the role of recycled residual slab component in the mantle source (Safonova et al., 2008). An OIB-like mantle enriched by ancient subducted and recycled oceanic crust gave rise to a source with an EM I signature that eventually supplied the magma parental to the Rajahmundry basalts. The mantle source enrichment processes were dominantly controlled by input from ancient pelagic sediments derived from subducted slabs (retaining HFSE such as Nb and Ta) that mixed with the OIB source region in the lower mantle and imparted distinct HFSE enrichment to the source. Nb/U ratio is not affected by fractional crystallization or partial melting and remains constant in MORB and OIB (Nb/U = 47 ± 10) reflecting similar values in depleted and enriched mantle reservoirs (Taylor and McLennan, 1985). Nb/U ratios (14–45) of RTB are lower than that of MORB and OIB and this particular feature reflects the addition of U back to the deep plume sources by recycling of ancient subducted crustal components (Plank and Langmuir, 1998; Condie, 2001).

The RTB shows enrichment in incompatible elements and positive Nb anomalies in the multi-element patterns which are characteristic features of plume-derived basalts of both oceanic and continental settings (Lightfoot et al., 1993; Wooden et al., 1993; Reichow et al., 2005; Xu et al., 2007; Safonova and Santosh, 2014; Simonov et al., 2014). Zr/Ba ratio has been considered as an effective parameter to distinguish lithospheric sources (Zr/Ba: 0.3–0.5) from asthenospheric sources of parent melt (Zr/Ba: >0.5; Menzies et al., 1991; Kürkcüoglu, 2010). The Zr/Ba ratios of RTB ranging from 0.51 to 3.24 and Zr/Hf ratios varying between 37 and 41 clearly indicate involvement of asthenospheric mantle sources in the melting process. Trace element ratios such as Zr/Nb, Zr/Y, Nb/Y provide viable petrogenetic clues to trace the plume signature in the genesis of Rajahmundry basalts. It has been suggested that plume derived basalts have lower Zr/Nb ratios in comparison with N-MORB (Zr/Nb: >301). A relatively lower range of Zr/Nb ratios (11–16) of Rajahmundry samples suggest a plume origin for the parental magma.

Flood basalt magma composition is modified by the composition of the plume source and the processes associated with melting and migration of melt to the surface. The continental lithospheric mantle and continental crust play important role in the genesis and evolution of CFB magmas (Song et al., 2008). The geochemical characteristics of RTB show evidence of minimum contamination by granitic continental crust during ascent of magma. Therefore, the importance of continental lithosphere in the generation of Rajahmundry basalts needs to be assessed. The conjunction of low Nb/Ta with high Zr/Hf and Zr/Sm ratios in comparison with primitive mantle values (17, 36 and 25 respectively) accounts for hydrous metasomatism of the mantle indicating an interaction between an upwelling plume head and a LILE-LREE enriched SCLM metasomatized by ancient subduction processes. The higher Th/Yb values and its relationship with Nb/Yb (Fig. 8C) provide evidence of lithospheric involvement. The plume–lithosphere interaction in the formation of RTB can be explained by the high melt retention and wall–rock interaction process suggested by Green and Falloon (1998) where mantle plumes extract incompatible trace elements from the lithospheric mantle during ascent. The HFSE enriched mantle plume ascended from the lower mantle and interacted with the SCLM causing LILE and LREE enrichment. However, it has to be considered that the subduction-metasomatized, LILE-LREE enriched continental lithospheric mantle is not the only source of the Rajahmundry basalts that erupted in continental intraplate settings. Rather, integrated petrological and geochemical attributes suggest that an interaction between ascending plume carrying an enriched mantle (EM I) signature and the continental lithospheric mantle enriched by ancient subduction processes provides a potential magma source for the generation of Rajahmundry basalts. The plume source contributes the enriched mantle (EM I) signature and the continental lithospheric mantle imparts the LILE and LREE abundances into the parent magma which was derived by 3–5% partial melting of mantle in the compositional range of spinel to garnet peridotite at depths between 60 and 100 km. Subsequent polybaric fractional crystallization of the melt generated the Rajahmundry basalts.

7.2. Evaluation of tectonic setting

Basaltic magmas are known to be emplaced in a variety of tectonic settings including intraplate continental or oceanic environments, intraplate rift zone settings, fast and slow spreading mid-oceanic ridges, island arcs, and back-arc basins (Pearce and Cann, 1973; Pearce and Norry, 1979; Pearce, 2008). The RTB are mid- to high-Ti basalts (TiO_2>1.5 wt.%) having Al_2O_3/TiO_2 ranging from 3.88 to 6.83 compared with island arc basalts (15–25) and MORB (10–15) which suggests their generation in an intraplate continental tectonic setting (Regelous et al., 2003; Manikyamba et al., 2004; Safonova, 2009). Incompatible trace element abundances and HFSE ratios serve as suitable parameters to discriminate the tectonic environment for the eruption of basaltic magmas. The Rajamundry basalts cluster in the field of within plate basalts (WPB) and exhibit E-MORB affinity in terms of Hf/3–Th–Ta relationship (Fig. 9). Incompatible trace element abundances of RTB (Fig. 5) exhibit positive Th, negative K and Ti anomalies which are conformable with their generation in rift-controlled, intra-continental tectonic setting. Therefore, the geochemical attributes of RTB provide evidence for their *in situ* intrabasinal eruption through fault-controlled fissures and this observation fits into the regional geological framework of Pangidi-Rajahmundry Basin in the east coast of India.

Two different schools of opinions exist for the origin and emplacement of RTB; one suggesting long-distance transportation of lava flows from Deccan Traps of western India to the east coast along Cretaceous palaeovalleys either through Krishna or Godavari rivers (Baksi et al., 1994; Jay and Widdowson, 2008) and the other view supporting intrabasinal eruption of lavas through fault-controlled fissures in an extensional tectonic milieu (Nageswara

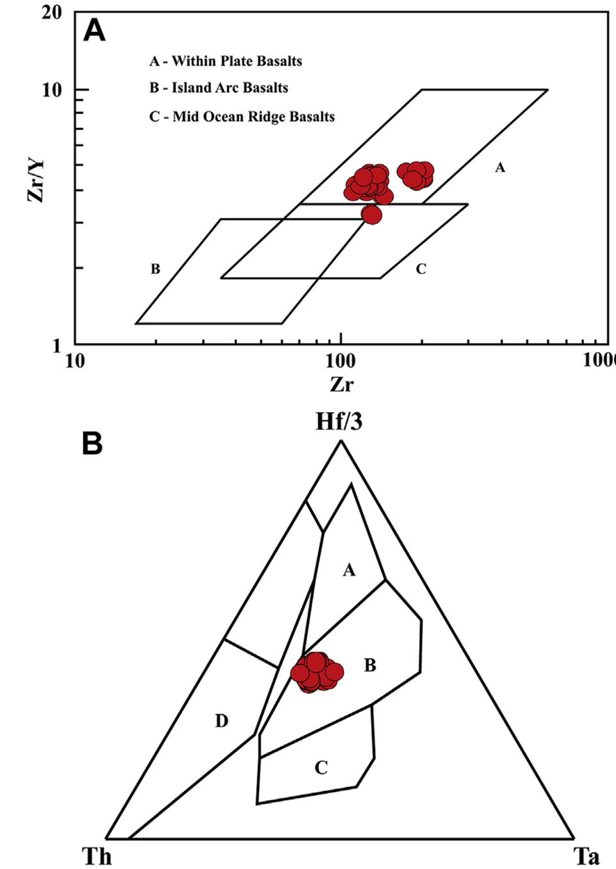

Fig. 9. (A) Zr vs. Zr/Y tectonic discrimination discrimination diagram (after Pearce and Norry, 1979) showing the plots of Rajahmundry basalts in the field of within plate basalts (WPB). (B) Rajahmundry samples displaying an E-MORB like intraplate tectonic affinity in terms of Hf/3–Th–Ta compositional variations (after Wood, 1980). A: N-MORB, B: E-MORB, C: WPB, and D: Supra Subduction Zone (SSZ).

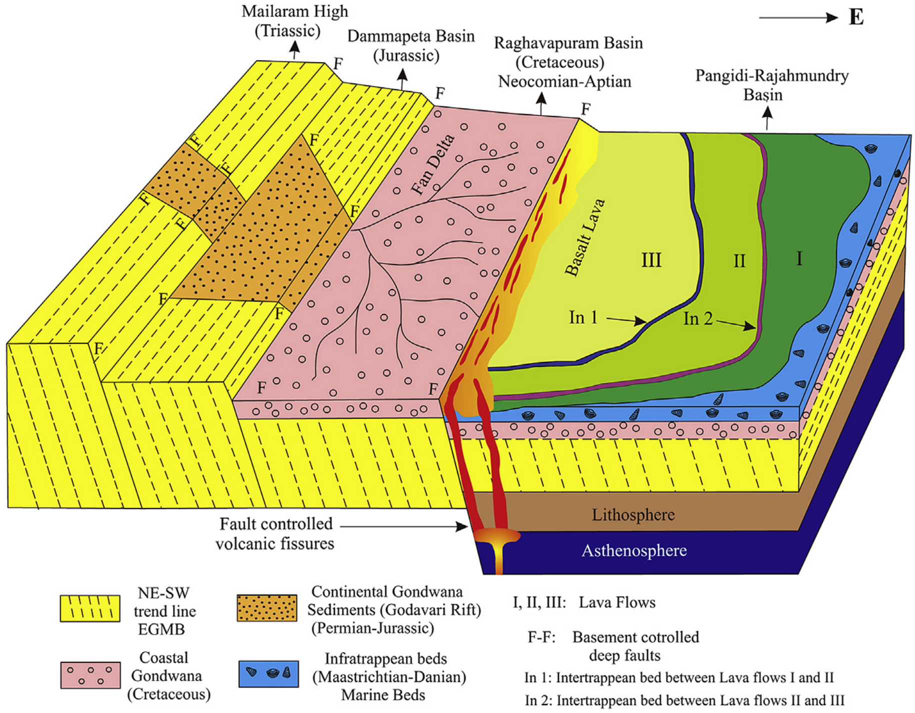

Fig. 10. A schematic model showing the interaction between the plume and lithospheric mantle followed by fault-controlled intrabasinal eruption of Rajahmundry Trap Basalts (RTB).

Rao et al., 2008; Lakshminarayana et al., 2010). The hypothesis of long-distance lava transportation along palaeovalleys has also correlated RTB with Deccan Traps of Kolhapur Formation in the western India. However, critical evaluation of palaeotectonic reconstruction and paleogeographic setting (Lakshminarayana et al., 2010) suggests Mesozoic uplift of the Eastern Ghat mobile belt (EGMB). Consequent change in palaeodrainage in the K-G Basin, fault-related tectonic movements in the Godavari rift and associated shifts in paleocurrent directions of Cretaceous sedimentation do not offer any evidence for the existence of a long-distance Cretaceous palaeo- valley connecting western India to the east coast. Baksi and Brahmam (1985) proposed that the Rajahmundry Traps extruded through local faults and rifts and they were coeval with the main episode of Deccan volcanism (65 Ma). However, Baksi (1994) suggested a marginally younger 64.0 $\pm$ 0.4 Ma age for RTB in comparison with average age for Deccan volcanism (65.5 $\pm$ 0.5 Ma). Long-distance transportation of lava flows from western Deccan to the east coast would result in considerable crustal contamination of the lavas. However, the Ba contents (54–262 ppm) and Nb/Th (8–13) ratios for the three lava flows of RTB suggest (i) minimum contamination of plume-derived melts by granitic continental crust and (ii) assimilation of Ba-rich estuarine to shallow-marine sediments of Infra- and Intertraps by the lava flows. No lateral variation of bulk rock chemistry, which is a possible consequence of long-distance flows, is observed in the studied lava flows which again indicate that these are not eastward extension of Deccan Trap lavas of Western Ghats.

Venkayya (1949) and Pascoe (1950) reported a $\sim$10–30 m thick lava flow separated from two flows of variable thickness by a $\sim$1–4 m thick intertrappean bed consisting of limestone and marl. Drill cores studies of basalt from southwest and south of Rajahmundry Traps and of interetrappean sediments recovered at Narasapur (70 km south of Rajahmundry) suggest that three basaltic lava flows occur at depths of $\sim$3.3 km. These lava flows initially covered larger areas and appear to have formed in a subaqueous environment during late Masstrichtian (Govindan, 1981). The $\delta^{18}O$ values (6.3–7.3‰) for RTB are not resulted from crustal contamination and have been attributed to interaction of basalt with shallow-marine water (Pascoe, 1950; Baksi et al., 1994). These observations support the present study of the RTB from the Gowripatnam and Duddukuru quarries comprising lower, middle and upper flows separated by intertrappeans I and II. The lower flow of RTB erupted over Infratrappean beds of sandstone, clay and limestone representing the late Cretaceous Tirupati Formation. The physical volcanological features like radial jointing, rootless cones, brecciated fragments and presence of fossiliferous limestone and marl blocks suggest eruption of the lower flow as hydrovolcanic explosion in a shallow marine environment. Radial jointing pattern (Fig. 2C) in the lower flow gives rise to rosettes which depict distortion in the cooling isotherm due to percolating water through cracks and fractures (Bondre et al., 2004, 2006; Duraiswami et al., 2004; Jay, 2005). Patches of limestone occurring in the lower part of the middle flow and absence of characteristic volcanological features reflect a relatively quiet mode of eruption over intertrappean I in a shallow marine to estuarine environment. The upper flow of RTB erupted over intertrappean II is predominantly made of red clay/red bole.

A schematic diagram (Fig. 10) illustrates the late Mesozoic–early Cenozoic faults and subsequent basin formation along the east coast of India. The Mailaram high (Triassic) was an uplifted block and a catchment area for the Cretaceous fan delta sediments along the east coast of India (Lakshminarayana, 2002). Extensional tectonic activities along this Mailaram high gave rise to the Dammapeta (Jurassic), Raghavapuram (Cretaceous) and Pangidi-Rajahmundry (Cretaceous–Tertiary) basins (Fig. 10). The westward marine transgression during Maastrichtian (Infratrappean beds at Duddukuru) was delimited by the fault controlled EGMB ridges (Fig. 10). There were no palaeovalleys linking the western India to the east coast during Cretaceous. The RTB lavas erupted through fault controlled fissures in the Pangidi-Rajahmundry Basin

(Fig. 10) during Cretaceous–Tertiary. The present day Krishna and Godavari valleys linking the western India to east coast came into existence during Miocene (Krishnan, 1968; Ramakrishnan and Vaidyanadhan, 2008). Therefore, evaluation of tectonic setting and emplacement conditions for RTB in terms of regional geological framework suggests fault-controlled *in situ* eruptions in an intrabasinal setting.

7.3. Comparison with Deccan Trap Basalts

The Rajahmundry Trap basalts have relatively higher MgO contents (6.19–13.12 wt.%) and lower Zr (109–202 ppm) than that of Deccan Trap Basalts from Dhanu-Nasik-Igatpuri (MgO: 4.83–5.55 wt.%; Zr: 152–230 ppm), Indore-Khargaon (MgO: 3.79–5.8 wt.%; Zr: 155–277 ppm), Toranmal (MgO: 2.98–7.11 wt.%; Zr: 82–238 ppm), Bijasan Ghat section (MgO: 5.64–7.09 wt.%; Zr:119–167 ppm) and Panna-Jabalpur-Seoni-Nagpur (MgO: 4.34–6.3 wt.%; Zr: 111–250 ppm) (Mahoney et al., 2000; Sheth et al., 2004; Chatterjee and Bhattacharji, 2008; Shrivastava et al., 2008) which suggest that the RTB shows much lesser degree of crustal contamination than that suffered by the Deccan basalts. Further, the granitic continental crust served as one of the major contaminants of Deccan lavas during their migration through crust. However, for the Rajahmundry lava flows, the shallow-marine to estuarine infratrappean and intertrappean sediments contaminated the rising magma. Fractional crystallization has been suggested as an important differentiation process operated during the petrogenetic evolution of the continental flood basalt magmas as observed for basaltic lava flows of Deccan Traps from Western Ghats section (Mahoney, 1988; Melluso et al., 2004, 2006); Bijasan Ghat section of Satpura Range (Sheth et al., 2004), Toranmal (Mahoney et al., 2000), Jabalpur and Seoni areas (Shrivastava et al., 2008; Kumar and Shrivastava, 2009), lava flows of Indore-Khargaon, Mhow-Chikaldara (Chatterjee and Bhattacharji, 2008) and Emeishan flood basalts of China (Song et al., 2006, 2008; Lai et al., 2012), flood basalts of Parana, Brazil (Hawkesworth et al., 1992), Wrangellia flood basalts, North America (Lassiter et al., 1995). The MgO contents (6.2–13.12 wt.%) of RTB show a relatively higher range, while Mg# values (29–50) are consistent with that of Deccan lava flows from Dhanu-Nasik-Igatpuri (MgO: 4.83–5.55 wt.%; Mg#: 42–47), Indore-Khargaon (MgO: 3.79–5.8 wt.%; Mg#: 39–51), Toranmal (MgO: 2.98–7.11 wt.%; Mg#: 32–60), Bijasan Ghat section (MgO: 5.64–7.09 wt.%; Mg#: 48–53) and Panna-Jabalpur-Seoni-Nagpur (MgO: 4.34–6.3 wt.%; Mg#: 39–52) indicating a differentiated and evolved chemistry marked by extensive fractional crystallization of parent magma.

It has been suggested that continental flood basalt (CFB) magmas are products of mantle plume activity and they represent a spectacular manifestation of the Earth's internal activity in terms of (i) rising of low viscosity, hot mantle material from the core-mantle boundary in the form of a plume, (ii) decompression melting of the plume-head and interaction between plume-derived melts and sub-continental lithospheric mantle (SCLM), (iii) impingement and incubation of plume-head at the base of continental lithosphere and magmatic underplating at the lithospheric base, (iv) partial melting of magma modified by SCLM and plume components carrying enriched mantle characters, (v) magmatic differentiation and polybaric fractional crystallization of magma, and (vi) eruption of Fe-rich, tholeiitic flood basalts through reactivated pre-existing rift systems or newly generated rifts and fractures initiated by upwelling plume-head (Campbell and Griffiths, 1990; Turner and Hawkesworth, 1995; Silver et al., 2006; Garfunkel, 2008). Major CFB provinces of the world, e.g. Siberia (Lightfoot et al., 1993), British Tertiary Volcanic Province (Thompson and Morrison, 1988), Ethiopia (Thompson et al., 1983), Parana-Etendeka (Gibson et al., 1997), Emeishan (Song et al., 2008) and Deccan (Mahoney, 1988) preserve geochemical signatures of several contributing sources like plume, asthenosphere, SCLM and continental crust that played significant role in their origin and evolution. The geochemical signatures of RTB suggest that the magma generation processes are similar to that of Deccan Trap basalts in terms of plume and lithospheric mantle involvement. However, the Deccan lavas were dominantly contaminated by upper continental granitic crust, while the RTB lavas primarily assimilated infra- and inter-trappean sediments.

Geochemical and tectonic interpretations suggest that the Rajahmundry Trap basalts were formed by intrabasinal volcanism through fault-controlled fissure eruptions in continental intraplate setting and were associated with upwelling plume activity, continental rifting, break-up and drifting as generally observed in Continental Flood Basalt (CFB) magmatism (Sheth et al., 2009; Vanderkluysen et al., 2011). Out of two possibilities regarding the spatial and temporal correlation with Deccan Traps, the present study is in conformity with contemporaneous *in situ* eruption of RTB lava flows in an intrabasinal setting with geochemical characteristics resembling that of Deccan lavas, except the role of contamination by granitic continental crust which is minimum for RTB compared to Deccan Traps, and does not accord with the long-distance transportation of lava flows along palaeochannels. Thus, in a broader perspective, it can be inferred that during the Cretaceous, decompression melting of rising Reunion plume-head (related to 66–65 Ma Deccan volcanism) may have supplied thermal energy and interacted with the lithospheric mantle for producing Rajahmundry basalts. Extensional episodes related to Reunion plume-impingement beneath Indian continental lithosphere resulted into rifting and fracturing during the Cretaceous–Tertiary (K/T boundary) transition which generated NW–SE and NE–SW regional faults. These fault systems provided pathways for the outpouring of basaltic lava flows that flooded the K-G Basin and gave rise to the RTB.

8. Conclusions

(1) The lower, middle and upper lava flows of RTB represent three distinct phases of lava emplacement; each episode of lava eruption was punctuated by the deposition of intertrappean I and intertrappean II. The lower and middle flows were formed by hydromagmatic eruptions during marine transgression in a shallow-marine to estuarine environment, whereas the upper flow erupted during a phase of marine regression.

(2) The lava flows of RTB are three-phenocryst basalts produced by 3–5% melting of the mantle source at variable depths from spinel to garnet peridotite compositional range.

(3) The Rajahmundry Trap Basalts (RTB) show geochemical conformity with a mantle plume source having EM I signature and their petrogenetic evolution is marked by contributions from plume-derived melts and lithospheric mantle.

(4) The RTB are analogous to Deccan Trap Basalts in terms of petrography, geochemical attributes, plume-related enriched mantle source characters and petrogenetic processes including mantle melting conditions and fractional crystallization of the parent magma, except their minimum contamination by granitic continental crust and prominent input from shallow-marine to estuarine Infra- and Inter-trappean sediments.

(5) RTB show no possibility of being southward extension of Deccan lava flows. The regional tectonic implications and associated geochemical signatures of RTB do not conform to their emplacement as long-distance, intracanyon flows of Deccan Traps and point towards fault-controlled, *in situ* eruptions of RTB in an intrabasinal tectonic setting.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2014.05.003.

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